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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE PERFORMANCE OF A SINGLE TUBULAR COMBUSTOR AT PRESSURES UP TO 12 ATMOSPHERES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PRELIMINARY INVESTIGATION OF THE PERFORMANCE OF A SINGLE TUBULAR COMBUSTOR AT PRESSURES UP TO 12 ATMOSPHERES

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SUMMARY

The effects of combustor operation at conditions representative of those encountered in high pressure-ratio turbojet engines or at high flight speeds on carbon deposition, exhaust smoke, and combustion efficiency were studied in a single tubular combustor. Carbon deposition and smoke formation tests were conducted over a range of combustor-inlet pressures from 33 to 173 pounds per square inch absolute and combustor reference velocities from 78 to 142 feet per second. Combustion efficiency tests were conducted over a range of pressures from 58 to 117 pounds per square inch absolute and velocities from 89 to 172 feet per second.

Total carbon deposition increased rapidly with increases in inlet-air pressure and velocity and increased slightly with increases in fuel-air ratio. Smoke formation increased appreciably with increases in pressure and fuel-air ratio but not significantly with increases in combustor reference velocity. Combustion efficiency varied between 88 and 100 percent over the entire range of conditions covered and generally decreased with decreasing pressure and increasing velocity. No limiting values of heat-release rate, in Btu per hour per cubic foot of combustor volume per atmosphere, were obtained at the highest pressure condition as velocity and fuel flow were increased to conditions limited by the capacity of the test facility.

INTRODUCTION

Trends in present turbojet-engine design are directed toward higher flight speeds and the use of higher compressor pressure ratios which, combined with improvements in compressor design, are resulting in higher combustion-chamber pressures and greater air-flow rates per unit cross-sectional area. A preliminary investigation of the effects of these design trends on the turbojet combustion process is reported herein.

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Severe carbon deposition and smoke problems have been encountered with current development engines operating at sea-level pressure ratios as high as 12. Carbon deposition in the combustor may have detrimental effects on performance by altering fuel-spray or air-entry patterns and causing distortion or warping of combustor liner walls. Smoke formation, on the other hand, does not generally impair engine performance but may be undesirable from a tactical or a nuisance standpoint. Published information concerning the effects of combustor-inlet pressure and velocity on carbon deposition and exhaust-smoke formation is somewhat meager. Investigations conducted by the Shell Development Company 3124
with a small-scale single combustor (unpublished data) indicated that the amount of carbon deposited per unit weight of fuel burned increased with increasing pressure to a maximum value and then decreased with a further increase in pressure. In the reference investigation, air-flow rate was held constant; thus, inlet-air velocity decreased with increasing inlet-air pressure. Information from reference 1 indicates that the variations in carbon deposition with pressure are partly dependent upon variations in inlet-air velocity. Data from references 2 and 3 show an increase in carbon deposition per unit of fuel burned with an increase of inlet-air pressure. Exhaust-smoke formation is also affected by changes in inlet-air parameters as indicated by data from reference 4; the most pronounced effect was the large increase in smoke resulting from increases in pressure.

Combustion efficiency, in general, has been found to decrease with increasing inlet-air velocity (refs. 5 and 6) and with decreasing inlet-air pressure and temperature. For turbojet engines operating at low compressor pressure ratios, the effect of these inlet variables on efficiency may be expressed, with fair accuracy, by the empirical equation $\eta_b = f\ (V_r/PT)$ where η_b is the combustion efficiency and P, T, and V_r are the combustor-inlet pressure, the inlet temperature, and the reference velocity, respectively (refs. 7 to 9). If this relation is valid for high pressure operation, then increases in pressure may permit corresponding increases in velocity without affecting combustion efficiency.

The investigation reported herein was conducted to determine the effect of inlet-air pressure, reference velocity, and fuel-air ratio on carbon deposition, smoke formation and combustion efficiency in a single tubular turbojet combustor. Carbon deposition and smoke-formation tests were conducted at pressures from 33 to 173 pounds per square inch absolute and combustor reference velocities from 78 to 142 feet per second. Combustion-efficiency data were obtained at combustor-inlet pressures from 58 to 117 pounds per square inch absolute and over a wide range of velocities and fuel-air ratios.

APPARATUS

<u>Combustor installation</u>. - A production model J33 inner liner and dome were installed in a high-pressure test unit (fig. 1) connected to the laboratory 450-pound-per-square-inch air-supply system and to an atmospheric-exhaust muffler. The high-pressure combustor housing was similar to a J33 combustor housing except that circular inlet and exhaust transition sections were used. The J33 configuration was selected for the high-pressure tests because of the large amount of carbon-deposition data previously accumulated with this type of combustor and also because of its relatively small size and, hence, its low air-flow requirements. Two sets of easily disconnected flanges (fig. 1) were installed to facilitate removal of the combustor from the test unit. The number of flanged joints in the test ducting was kept at a minimum in order to avoid leaks and warping. A high-pressure flexible coupling at the inlet of the test unit was used to absorb thermal expansion (fig. 1). In order to improve the velocity profile of the air entering the combustor, a flow-straightening screen was placed at the inlet end of the test section.

Air-flow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the combustor; fuel flow was controlled by means of a needle valve located downstream of a high-pressure fuel pump. No air-preheating equipment was available for this investigation; the combustor inlet-air temperature varied with the discharge temperature from the five-stage, intercooled, air-compressor system. Four water-spray nozzles, spaced axially in the exhaust ducting and supplied by a high-capacity, high-pressure pump reduced the temperature of the exhaust gases to a safe level.

During the carbon and smoke tests three sizes of fuel nozzles were utilized in order to achieve the desired flow rates. For the lowest fuel-flow rates investigated, a standard hollow-cone, swirl-type nozzle with a nominal flow capacity of 40 gallons per hour (pressure, 100 lb/sq in.) and a spray angle of 80° was used. For intermediate flow rates, a similar nozzle with a nominal flow capacity of 60 gallons per hour (pressure, 100 lb/sq in.) and a spray angle of 70° was used. For the highest flow rates, a 60-gallon-per-hour nozzle was modified by enlarging the discharge orifice to provide a flow capacity of 110 gallons per hour at a pressure of 100 pounds per square inch; the spray angle was about 75°. The 60- and the 110-gallon-per-hour nozzles were used in the combustion efficiency tests.

<u>Instrumentation</u>. - Air-flow rates were measured by square-edged orifice plates installed according to A.S.M.E. specifications. The pressure drop across the orifice was measured by a commercial pneumatic differential pressure transmitter. The output of the transmitter was measured by a mercury manometer. Fuel flow was measured by calibrated

rotameters located upstream of the high-pressure fuel pump. Inlet-air temperatures were measured by two enclosed single-junction iron-constantan thermocouples located at plane x-x (fig. 2). The junctions were at centers of equal areas. Exhaust-gas temperatures were measured by eight two-junction chromel-alumel thermocouple rakes located at station B-B (fig. 2); individual junctions were located at centers of equal areas. The thermocouple supports at the exhaust were made of brass and were cooled by a stream of high-pressure air bled from the combustion-air supply line upstream of the orifice (fig. 3). By means of a suitable switching arrangement, either individual temperatures or an average temperature of all exhaust-gas thermocouples could be obtained. Inlet- 3124
air and exhaust-gas total pressures were measured by four three-point total-pressure probes at plane y-y and station A-A (fig. 2). The probes were located at centers of equal areas. The inlet-air probes were connected to a common manifold, as were the exhaust probes; the two manifold pressures were measured by two strain-gage-type pressure cells. The pressure cells and all thermocouples were connected to self-balancing potentiometers. Detailed views of the construction of the thermocouples and pressure rakes are presented in figure 3.

The relative quantity of smoke contained in the combustion exhaust gases was determined with a smoke meter that consisted essentially of an air-cooled filter press through which a metered volume of exhaust gas was drawn. Smoke particles suspended in the gas were deposited on a paper filter disk. A transmission densitometer, which measured the optical density of the smoke-covered filter disks, was used to give an indication of the amount of smoke deposited on the paper. The apparatus and the method of smoke determination are described more fully in reference 4. The exhaust-gas sample for determining the smoke density was obtained from one of the three-point total-pressure probes located at station A-A (fig. 2).

Fuel. - A production-type jet fuel, MIL-F-5624A grade JP-4 (NACA 52-288) was used in these investigations; chemical and physical properties of the fuel are presented in table I.

PROCEDURE

Carbon deposition and smoke. - Carbon deposition and smoke formation tests were conducted at the approximate combustor operating conditions shown in the following table:

Test condition	A	B	C	D	E
Inlet-air pressure, lb/sq in. abs	33	86	86	86	173.4
Inlet-air temperature, °F	240	240	240	240	240
Air-flow rate, lb/sec	2.78	6.84	6.84	12.4	13.8
Combustor reference velocity[a], ft/sec	80	80	80	140	80
Fuel-air ratio	0.0170	0.0170	0.0240	0.0170	0.0170

[a]Based on maximum cross-sectional area of combustor housing (0.267 sq ft) and inlet-air pressure and temperature.

These conditions were chosen (1) to be representative of operation of a turbojet engine with a pressure ratio of 12 at a flight Mach number of 1.8 and at altitudes from 35,000 to 70,000 feet, and (2) to provide comparisons of effects of pressure, velocity, and fuel-air ratio on carbon deposition and smoke. Because of the test-facility limitations previously noted, the inlet-air temperatures were appreciably lower than those encountered under actual full-scale engine operating conditions.

The inlet-air pressures and velocities at conditions A, B, and E
3124 simulated operation at altitudes of 70,000, 50,000, and 35,000 feet, respectively. Conditions A, B, and E differed only in pressure and air mass flow; conditions B and D, only in reference velocity and air mass flow; and conditions B and C, only in fuel-air ratio.

Prior to each test run, the combustor inner liner and dome assembly and the ignition plug were cleaned with rotating wire brushes and then weighed on a torsion-type balance. After a specified period of operation, during which the required operating conditions were held constant, the assembly and the ignition plug were reweighed. The difference in weight plus the weight of deposit on the fuel nozzle represented the total deposit reported herein.

Smoke measurements were made by first establishing continuous flow of exhaust gases from the sampling probe through the sampling system by means of a bypass line located immediately upstream of the smoke meter. After combustor operation had been stabilized at the desired conditions, a fixed volume of exhaust gas was passed through the smoke meter. The optical density of the smoke-covered paper was then determined with the transmission densitometer. The difference in readings between the smoke-covered and the clean filters was considered a measure of the amount of smoke in the sample and is referred to as "smoke density" in this report.

Combustion efficiency. - Combustion efficiency tests were conducted over a range of fuel-air ratios at the two inlet-air pressures and the range of combustor reference velocities shown in the following table:

Inlet-air pressure, lb/sq in. abs	58.4	117.6
Combustor reference velocity, ft/sec	89-166	93-172

The inlet-air temperature varied from 210° to 258° F.

Combustion efficiency is defined as the ratio of the actual enthalpy rise across the combustor (between plane x-x and station B-B (fig. 2)) to the total enthalpy supplied by the fuel and was computed by the method of reference 10.

Heat-release rates were computed as the heat output of the combustor in Btu per hour per cubic foot of combustor volume per atmosphere. The combustor volume was arbitrarily expressed as the product of the maximum cross-sectional area of the combustor housing and the distance from the fuel nozzle tip to the plane of the exhaust-gas thermocouples (fig. 2).

Instrument and apparatus check. - The use of high-pressure air and special instruments necessitated frequent checks for air leaks and constancy of calibration of the instruments. In some cases welded connections which had been tight at the beginning of operation were found to have developed leaks after several hours of high-pressure operation. 3124
In addition, a number of thermocouple and pressure rakes failed during the test program. Thus, before each run the combustor was pressurized and checked for leaks. With zero air flow, the pressure-cell readings were checked against an accurate Bourdon-type pressure gage and the zero reading of the differential pressure transmitter checked. With air flowing through the combustor, readings of the inlet and exhaust thermocouple and pressure rakes were inspected for consistency.

RESULTS AND DISCUSSION

The data obtained in the carbon deposition, smoke formation, and combustion efficiency tests are presented in table II.

Carbon Deposition

Significance of results. - It has been observed that carbon deposition increases with time in a reproducible manner during the first part of a test run. After some period of time, erosion and breaking away of the deposits tend to reduce the rate of formation of deposits and frequently cause erratic deposition results. The effect of test duration on carbon deposition was therefore first investigated in order to establish a standard test duration for subsequent tests. Tests were conducted in which carbon deposition was measured after runs of 1, 2, and 3 hours' duration. The results of these tests are presented in table II and figure 4, which shows that carbon deposition increased linearly with time for the durations examined. Although the effect of test duration was investigated at one condition only, the trend was considered adequately applicable to the other conditions investigated and, hence, a test duration of 2 hours was selected for subsequent tests. An indication of the reproducibility of test results may be obtained from the following table in which the results of a number of check tests are presented.

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Run (table II(a))	Carbon deposited, g	Average carbon deposition, g	Deviation from average, percent
4 5	2.8 2.4	2.6	7.7
6 7	12.2 10.4	11.3	8.0
8 9	27.2 29.9	28.6	4.7
10 11	26.7 22.8	24.8	7.9

A maximum deviation of 8 percent from the average was obtained. Average deviations of less than ±10 percent are generally considered satisfactory for carbon-deposition data.

Another factor which is of considerable importance in the evaluation of carbon deposition data is the fact that variations in the inlet-air parameters are accompanied by corresponding changes in fuel-flow rates. Inasmuch as carbon deposition increased linearly with time, suggesting that carbon formation may be a direct function of the amount of fuel burned, the effect of fuel-flow variations was minimized by expressing the data on a basis of weight of carbon formed per unit weight of fuel burned, in addition to an absolute basis of total carbon deposited.

Effect of pressure. - The effect of combustor-inlet total pressure on carbon formation at constant velocity and fuel-air ratio is shown in figure 5(a). Total carbon deposition increased almost linearly with increasing pressure; carbon deposition per unit weight of fuel burned also increased with increasing pressure but at a decreasing rate. Since the increase in pressure was accompanied by an increase in mass air flow, the fuel-flow rate was also increased. Thus, since carbon formation per unit weight of fuel burned did not increase at the same rate as the total carbon formation, only part of the increase in carbon deposition may be attributed to the effect of increased pressure, while the remainder should be considered a fuel-flow effect. The results, in general, were found to be consistent with those obtained by other investigators (e.g., refs. 1 to 3).

Effect of combustor reference velocity. - The effect of combustor reference velocity on carbon deposition at constant pressure and fuel-air ratio is shown in figure 5(b). Carbon deposition more than doubled as velocity was increased from 78 to 139 feet per second. On a basis of weight of carbon deposited per unit weight of fuel burned, carbon deposition increased only slightly with increasing velocity.

As in the case of inlet-air pressure, the increased velocity was accompanied by increased fuel-flow rate. Since the total carbon deposition increased much more rapidly than did the deposits per unit weight of fuel, a considerable part of the increased carbon deposition should be attributed to the increased fuel-flow rate. Velocity may be considered to affect carbon deposition by influencing (1) fuel-spray formation and impingement on combustor liner walls (ref. 11), (2) air admission distribution and, hence, local fuel-air ratios, and (3) erosion of deposits. The effect of velocity on carbon deposition would therefore be expected to vary with operating conditions. 3124

<u>Effect of fuel-air ratio</u>. - The effect of fuel-air ratio on carbon formation at constant inlet-air pressure and velocity is shown in figure 5(c). Total carbon formation increased with increasing fuel-air ratio. On a unit weight of fuel basis, however, carbon formation was essentially independent of fuel-air ratio; this indicates an effect of only fuel-flow rate on total carbon deposition. These results are consistent with the results obtained in the varying pressure and velocity tests which showed that the increased fuel flows which accompanied increases in pressure and velocity were partially responsible for the observed increases in carbon formation.

<u>Nature of carbon deposits</u>. - The largest quantity of carbon was deposited in the dome at most conditions investigated, with only a layer of soot in the first 5 to 8 inches of the liner. The primary-air louvers of the dome were nearly blocked in most cases. Both dull and glossy carbon deposits were obtained in the dome. The ignition-plug spark gap was never completely closed by carbon but was reduced considerably during the tests that resulted in the largest amounts of deposits.

Smoke Formation

The effects of variations in inlet-air pressure, combustor reference velocity, and in fuel-air ratio on smoke formation are shown in figures 6(a) to (c). In general, the magnitude of smoke density values obtained was too small to draw rigorous conclusions concerning the effect of these variables. The trends indicated an increase in smoke density with increasing pressure and fuel-air ratio. The effect of combustor reference velocity on smoke density (fig. 6(b)) is not considered significant. Data from reference 4 show that smoke density increases considerably with increasing pressure but that the effect of velocity on smoke varies greatly at different values of fuel-air ratio.

Combustion Efficiency

<u>Effect of fuel nozzles</u>. - Since the large range of fuel flows covered necessitated the use of two fuel nozzles of different capacity, it

was desirable to determine the effect of nozzle capacity on combustion efficiency. The results of these tests, presented in figure 7, show no marked effect of nozzle capacity on combustion efficiency. Although these tests were conducted at one condition only, it is considered probable that the use of two different fuel nozzles did not appreciably affect the results obtained at other inlet-air conditions investigated.

Effect of inlet-air parameters. - The combustion efficiencies obtained at two different pressures over a range of combustor reference
3124 velocities and fuel-air ratios are shown in figure 8. Combustion efficiency generally increased slightly with increases in fuel-air ratio, reached a maximum value, and then decreased with further increases in fuel-air ratio. Values of combustion efficiency were high, varying between 88 and 100 percent over the entire range of conditions covered. In order to isolate the effects of inlet-air pressure and velocity, the data from figure 8 were cross-plotted in figure 9, which shows the effect of pressure and velocity on combustion efficiency at two fuel-air ratios. In general, combustion efficiency decreased with increasing
CT-2 velocity and with decreasing pressure, a trend which is consistent with results previously obtained at lower levels of velocity and pressure.

Correlation of inlet-air parameters. - Combustion efficiencies obtained at lower pressure conditions have been found to correlate with the parameter V_r/PT, where V_r, P, and T are the combustor reference velocity, the inlet pressure, and the inlet temperature, respectively. In figure 10, this parameter is plotted against combustion efficiency for two representative fuel-air ratios. The limited number of test points shown in figure 10 seem to indicate that the data cannot be generalized over the wide range of pressures covered in these tests; that is, indications are that increases in pressure cannot be accompanied by proportional increases in velocity without some decrease in combustion efficiency. However, the range of combustion efficiency values obtained was too narrow to draw rigorous conclusions concerning the applicability of the correlations. Variations of as much as 10 percent have frequently been observed in the correlation.

Heat-release rates. - The maximum heat-release rate, a measure of the rate at which heat energy can be liberated in a given combustor volume, is important because it may establish the minimum size requirements of the combustor. In order to indicate the heat-release rates possible with a turbojet combustor of current design, heat-release values were computed from the data obtained in the combustion efficiency tests and are shown in table II(b). Values as high as 4,468,000 Btu per hour per cubic foot of combustor volume per atmosphere were obtained. Test facility limitations rather than combustor size prevented attainment of still higher heat-release rates. For comparison, the full-scale engine having combustors similar to the single-tube unit investigated attains a heat-release rate of 2,300,000 Btu per hour per cubic foot per atmosphere when operated at sea level, at rated engine speed, and at a flight Mach number of 0.6. This is a clear indication that heat-release rates far greater than those now obtained are possible with combustors of current design at high-pressure operating conditions.

Combustor total-pressure loss. - The effect of combustor reference velocity on combustor total-pressure loss, expressed as a percentage of the combustor-inlet total pressure ($\Delta P/P$) is shown in figure 11 for pressures of 58.4 and 117.6 pounds per square inch absolute and for an exhaust-gas to inlet-air temperature ratio of 2.0. This value corresponds approximately to the temperature-rise ratio required of the engine in order to maintain steady-state operation at the flight conditions simulated. Pressure drop ($\Delta P/P$) increased with increasing velocity; the rate of increase also increased with increasing velocity. As combustor-inlet total pressure was doubled, a slight increase in pressure drop ($\Delta P/P$) was observed over the entire range of reference velocity.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effects of high combustor-inlet pressures and velocities on carbon deposition, smoke formation, and combustion efficiency in a single tubular turbojet combustor:

1. Total carbon deposition increased rapidly with increases in inlet-air pressure and velocity and increased slightly with increases in fuel-air ratio.

2. Carbon deposition per unit weight of fuel burned was constant with time and fuel-air ratio but increased with increases in inlet-air pressure and velocity. However, since the total carbon deposition increased much more rapidly than the deposition per unit weight of fuel burned, the increase in carbon deposition with increasing pressure and velocity should be partially attributed to attendent increases in fuel flow.

3. Smoke formation increased considerably with increases in pressure and fuel-air ratio but not significantly with increases in combustor reference velocity.

4. Combustion efficiency varied between 88 and 100 percent over a range of combustor-inlet pressures from 58 to 117 pounds per square inch absolute and reference velocities from 89 to 172 feet per second. In general, combustion efficiency decreased with decreasing pressure and with increasing velocity.

5. An increase in combustor-inlet pressure accompanied by a proportionate increase in reference velocity resulted in a slight decrease in combustion efficiency; a previously developed correlation predicted no change in combustion efficiency at these conditions.

6. No limiting values of heat release rate, in Btu per hour per cubic foot of combustor volume per atmosphere, were obtained at the highest pressure condition as velocity and fuel flow were increased to conditions limited by the capacity of the test facility.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 10, 1953

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TABLE I. - PHYSICAL PROPERTIES OF MIL-F-5624A

GRADE JP-4

Fuel properties	NACA fuel 52-288
A.S.T.M. distillation, D86-46, °F	
Initial boiling point	139
Percent evaporated	
5	224
10	253
20	291
30	311
40	324
50	333
60	347
70	363
80	382
90	413
Final boiling point	486
Residue, percent	1.2
Loss, percent	0.7
Aromatics, percent by volume	
A.S.T.M. D-875-46T	10
Silica gel	10.1
Specific gravity	0.776
Viscosity, centistokes at 100° F	0.935
Reid vapor pressure, lb/sq in.	2.7
Hydrogen-carbon ratio	0.168
Net heat of combustion, Btu/lb	18,675
NACA "K" factor	278

TABLE II. - PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(a) Carbon deposit and smoke tests

Run	Combustor inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, °R	Air flow, lb/sec	Combustor inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °R	Combustion efficiency, percent	Fuel nozzle capacity, gal/hr	Run time, hr	Carbon deposited, g	Smoke density	Differential pressure across combustor, lb/sq in.
1	45.0	680	4.74	100	293.5	0.0172	1840	96.9	60	1	2.7	----	3.1
2	45.1	678	4.80	101	296.0	.0171	1840	97.6	60	2	4.3	----	3.1
3	44.6	681	4.74	101	293.0	.0172	1845	97.6	60	3	7.0	----	2.9
4	33.1	681	2.78	80	172.5	.0172	1835	96.5	40	2	2.8	----	1.0
5	33.1	678	2.76	79	173.0	.0174	1855	97.4	40	2	2.4	----	1.0
6	86.1	706	6.84	78	415.0	.0168	1865	99.3	60	2	12.2	----	3.0
7	86.1	704	6.81	77	414.0	.0169	1870	99.7	60	2	10.4	----	3.0
8	86.2	709	12.14	139	775.0	.0177	1875	95.0	110	2	27.2	----	11.7
9	86.2	706	12.17	139	790.0	.0180	1860	92.6	110	2	29.9	----	12.7
10	173.5	713	13.20	76	815.0	.0168	1865	99.1	110	2	26.7	----	6.4
11	173.6	707	13.64	77	813.0	.0166	1855	100.0	110	2	22.8	----	7.4
12	86.3	699	6.95	78	595.0	.0238	2270	99.2	60	2	16.7	----	----
13	32.7	680	2.84	82	171.0	.0167	1855	101.1	40	-	----	0.01	----
14	85.5	697	6.86	79	416.0	.0166	1880	102.8	60	-	----	.05	----
15	86.3	698	7.01	79	595.0	.0236	2285	101.0	60	-	----	.55	----
16	87.1	696	12.75	142	793.0	.0173	1875	98.5	110	-	----	.08	----
17	172.3	699	14.15	80	847.0	.0168	1870	101.6	110	-	----	.38	----

TABLE II. - PERFORMANCE DATA OF SINGLE TUBULAR COMBUSTOR

(b) Combustion efficiency tests

Run	Combustor-inlet total pressure, lb/sq in. abs	Combustor-inlet temperature, $^{\circ}R$	Air flow, lb/sec	Combustor-inlet reference velocity, ft/sec	Fuel flow, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, $^{\circ}R$	Combustion efficiency, percent	Fuel nozzle capacity, gal/hr	Combustion parameter $\frac{V_r}{PT}$ (ft, lb, sec, $^{\circ}R$ units)	Differential pressure across combustor, lb/sq in.	Heat release rate Btu/hr/atm/cu ft
18	58.4	676	5.38	88	128.5	0.0066	1122	80.0	60	15.5×10^{-6}	2.4	905,000
19	58.4	679	5.36	88	202.5	.0105	1426	98.1	60	15.5	2.5	1,556,000
20	58.4	682	5.32	90	300.0	.0157	1762	98.5	60	15.8	2.7	2,302,000
21	58.4	684	5.35	90	409.0	.0212	2097	98.1	60	15.7	3.0	3,145,000
22	58.3	688	6.96	117	248.5	.0099	1582	96.3	60	20.4	5.6	1,878,000
23	58.3	690	6.98	117	344.0	.0137	1850	98.9	60	20.4	4.7	2,673,000
24	58.5	692	7.00	119	423.5	.0168	1840	98.3	60	20.6	4.9	3,257,000
25	58.3	692	6.97	119	513.5	.0208	2060	98.2	60	20.6	5.1	3,958,000
26	58.3	693	8.37	139	275.0	.0091	1515	93.9	60	24.1	6.4	2,013,000
27	58.3	693	8.30	138	310.0	.0104	1400	94.1	60	23.9	6.4	2,290,000
28	58.3	702	9.01	156	243.5	.0075	1204	90.7	60	26.7	7.6	1,732,000
29	59.1	705	9.08	151	370.5	.0113	1446	91.3	60	25.4	8.5	2,609,000
30	58.3	706	9.07	157	518.0	.0159	1765	95.4	60	26.7	9.2	3,690,000
31	58.3	709	8.99	157	591.5	.0183	1880	92.9	60	26.6	9.4	4,311,000
32	58.3	708	9.94	173	399.5	.0112	1420	88.1	60	29.5	10.8	2,770,000
33	118.0	714	11.05	93	288.0	.0073	1190	96.1	110	7.69	5.8	1,081,000
34	117.6	714	11.17	95	408.5	.0102	1400	100.1	110	7.89	6.2	1,596,000
35	118.4	715	11.16	92	580.5	.0145	1690	100.5	110	7.58	6.5	2,350,000
36	117.6	715	11.10	95	743.0	.0186	1885	98.9	110	7.88	6.8	2,860,000
37	117.7	712	13.14	112	353.5	.0070	1216	97.0	110	9.33	8.2	1,254,800
38	119.3	718	12.99	107	511.0	.0109	1498	99.5	110	8.72	9.2	1,947,000
39	117.7	718	13.10	111	711.0	.0151	1760	98.9	110	9.12	9.9	2,733,000
40	118.5	718	12.99	109	931	.0199	2008	95.1	110	8.95	10.9	3,417,000
41	118.0	712	15.12	129	461	.0085	1312	97.0	110	10.7	11.0	1,729,000
42	119.2	713	14.99	123	583	.0108	1480	99.0	110	10.1	11.2	2,218,000
43	118.4	713	14.99	126	753	.0139	1680	98.4	110	10.5	11.9	2,845,000
44	120.0	714	14.87	122	968	.0179	1930	98.7	110	9.97	12.7	3,591,000
45	117.6	712	15.96	138	651.0	.0113	1515	89.5	110	11.6	13.5	2,508,000
46	118.4	712	15.98	135	778.0	.0135	1655	98.8	110	11.2	13.9	2,970,000
47	118.0	712	15.92	135	882.0	.0154	1770	98.4	110	11.3	14.5	3,367,000
48	117.6	712	15.97	137	1111.0	.0193	1980	95.9	110	11.5	17.1	4,148,000
49	117.7	710	18.38	157	476.0	.0072	1205	93.2	110	13.2	----	1,727,000
50	117.7	712	18.36	158	690.0	.0104	1415	93.2	110	13.2	----	2,499,000
51	117.7	714	18.42	159	927.0	.0140	1645	94.4	110	13.3	----	3,400,000
52	117.7	714	18.48	161	1108.0	.0166	1820	95.6	110	13.4	----	4,150,000
53	118.1	714	20.32	177	519.0	.0071	1180	89.0	110	14.8	----	1,790,000
54	117.7	714	20.46	179	850.0	.0116	1475	91.8	110	15.0	----	3,052,000
55	177.7	714	18.56	161	1200.0	.0180	1900	95.8	110	13.4	----	4,468,000
56	117.0	701	13.16	110	371.0	.0078	1242	94.3	60	9.38	8.0	1,362,000
57	118.2	702	13.21	110	520.0	.0109	1470	97.8	60	9.21	8.3	1,963,000
58	117.8	703	13.22	110	729.0	.0153	1753	98.1	60	9.30	9.0	2,772,000
59	117.4	708	13.22	110	819.0	.0172	1870	98.1	60	9.34	9.2	3,130,000

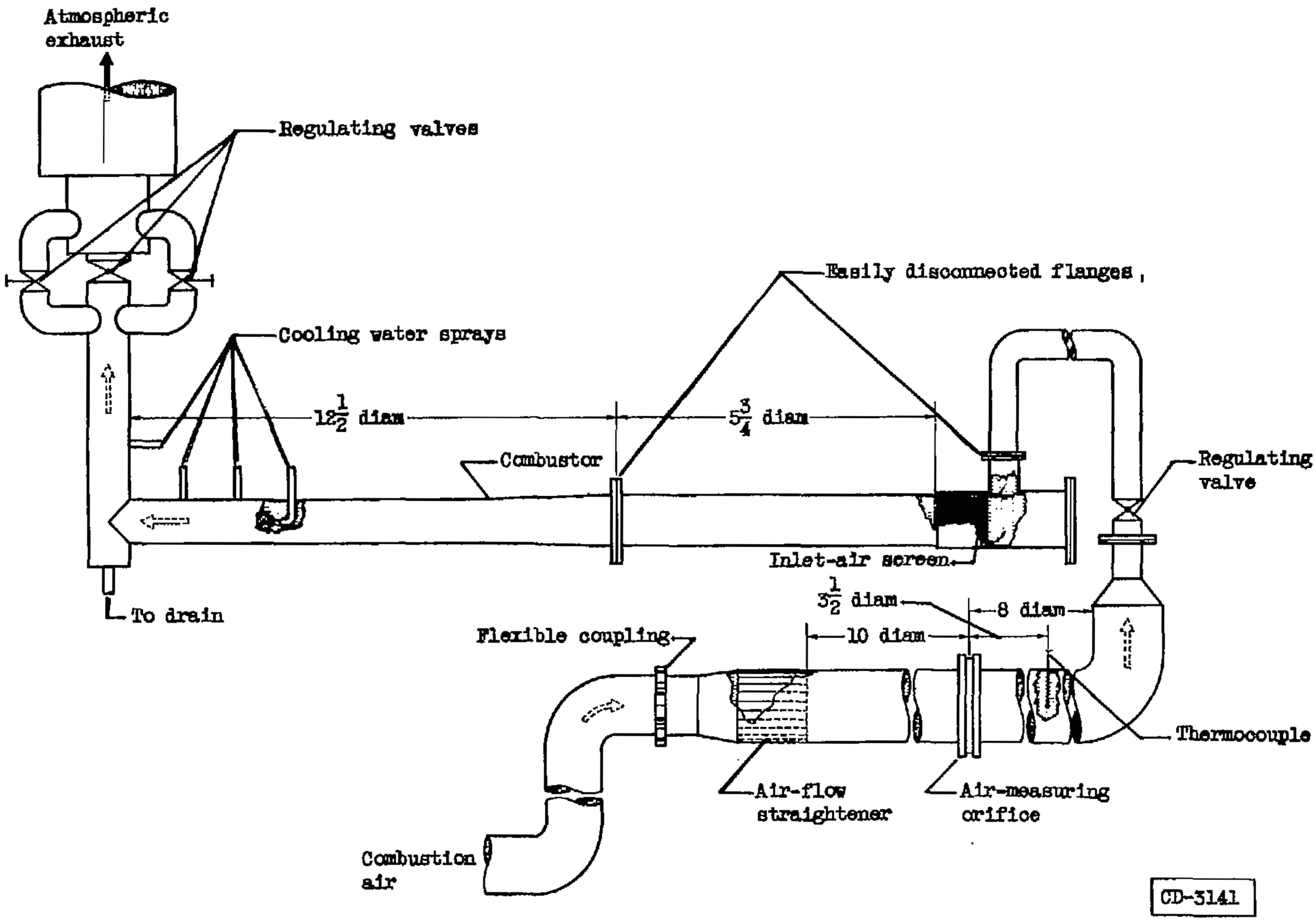

Figure 1. - Single-combustor installation and auxiliary equipment.

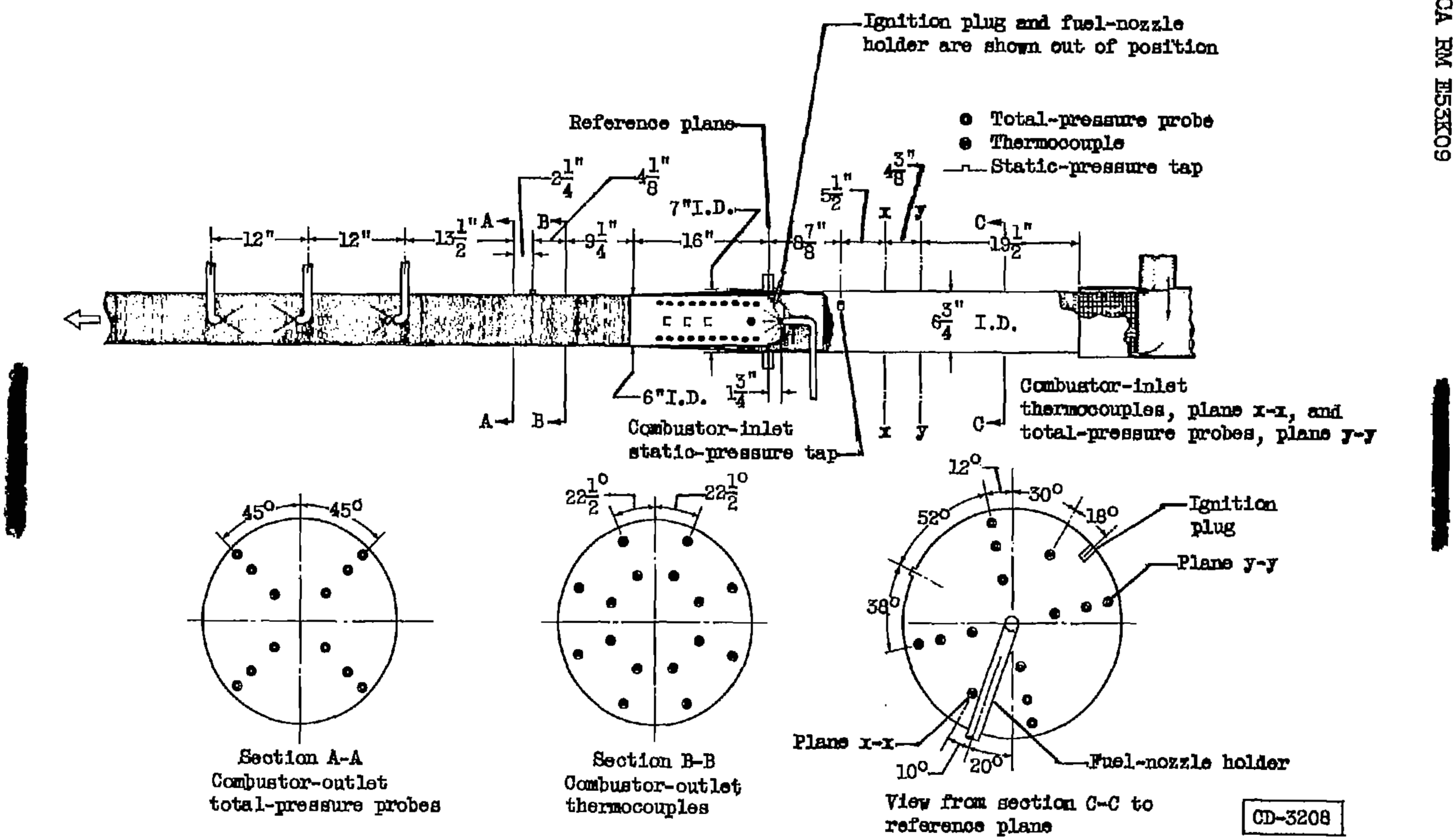

Figure 2. - Cross section of single-combustor installation showing auxiliary ducting and location of temperature- and pressure-measuring instruments in instrumentation planes.

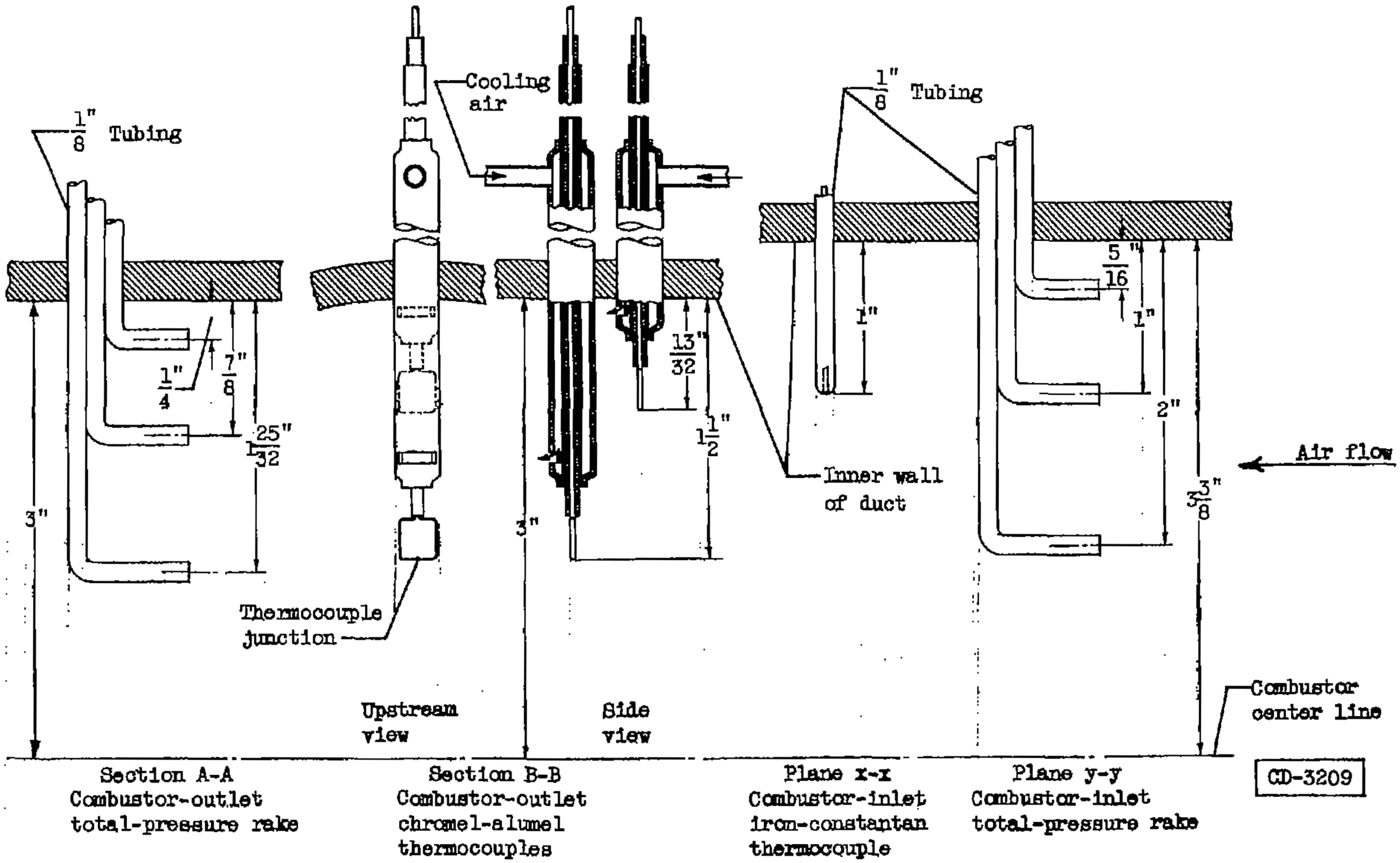

Figure 3. - Construction details of temperature-and pressure-measuring instruments.

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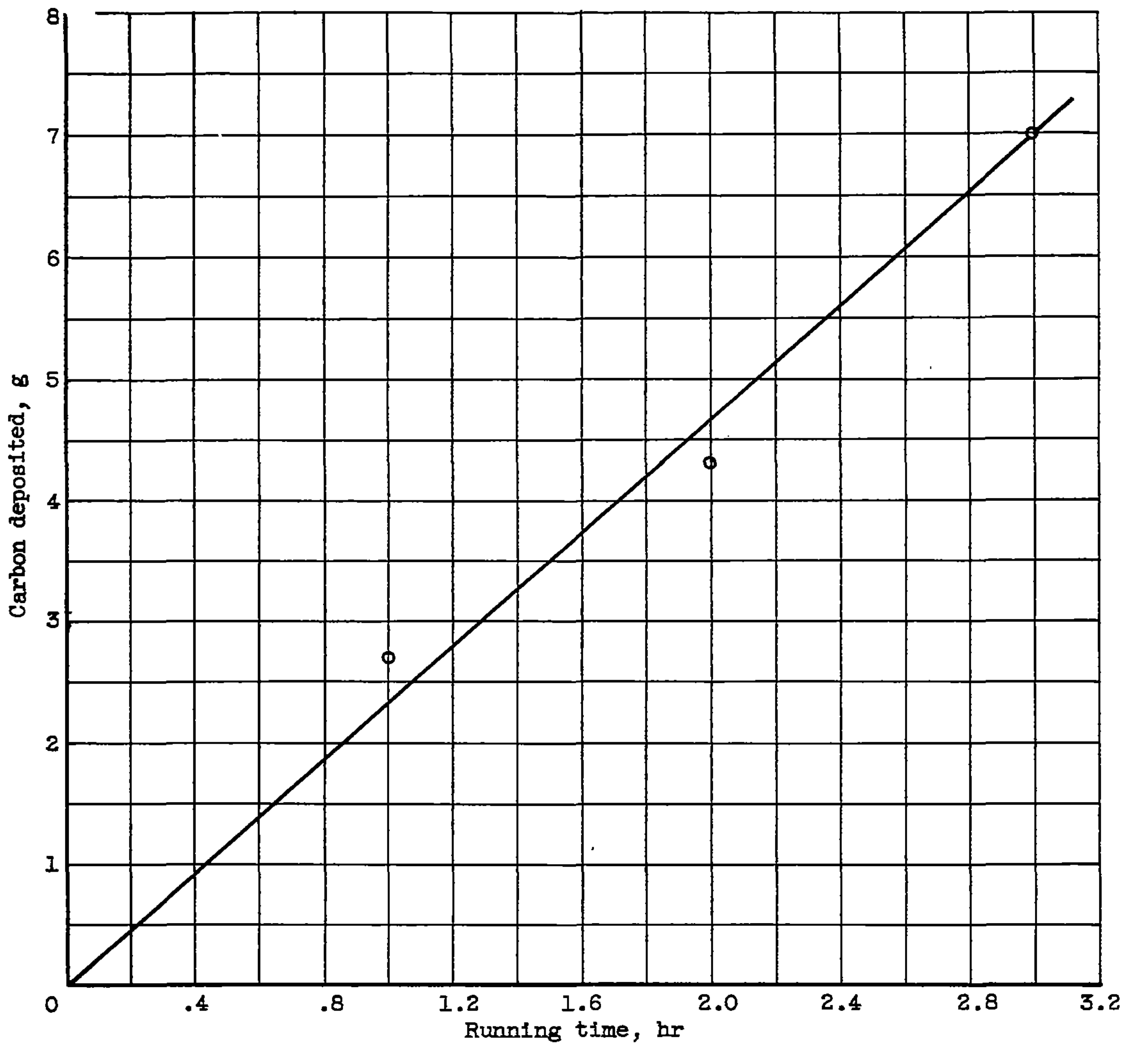
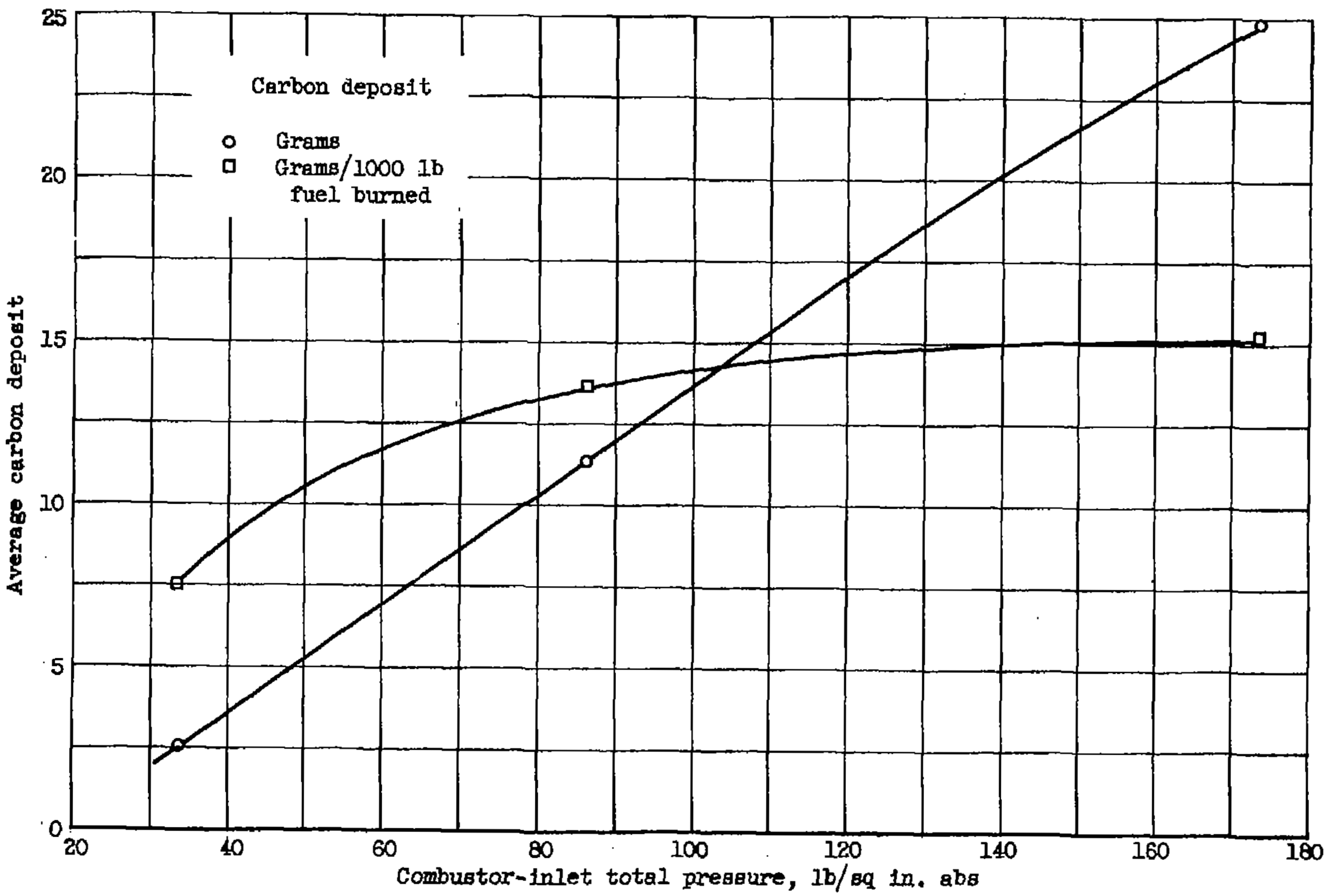
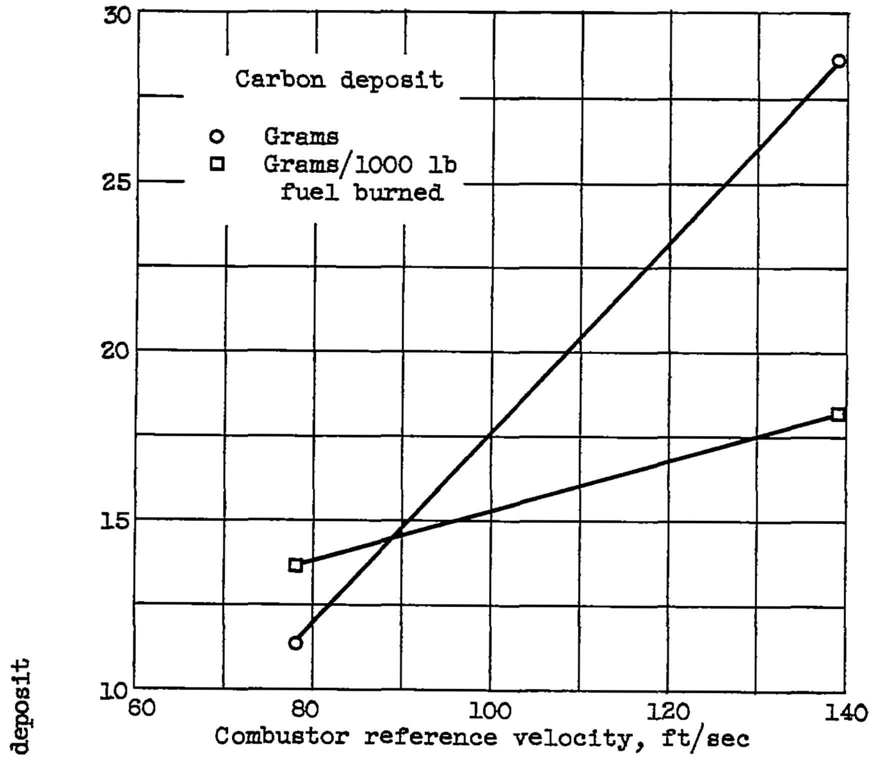


Figure 4. - Effect of running time on carbon deposition in single tubular combustor. Inlet-air pressure, 45.0 pounds per square inch absolute; inlet-air temperature, 220° F; combustor-inlet reference velocity, 101 feet per second; fuel-air ratio, 0.0172.

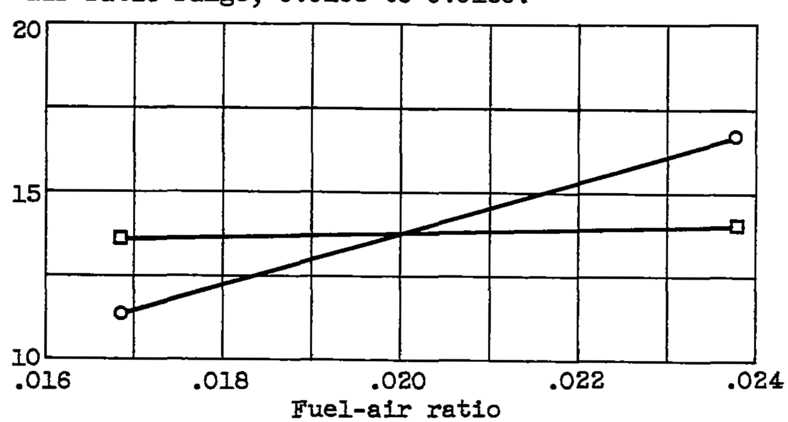


(a) Effect of combustor-inlet total pressure. Combustor reference velocity, 78 feet per second; inlet-air temperature range, 218° to 253° F; fuel-air-ratio range, 0.0166 to 0.0174.

Figure 5. - Effect of combustor conditions on carbon deposition in single tubular combustor.

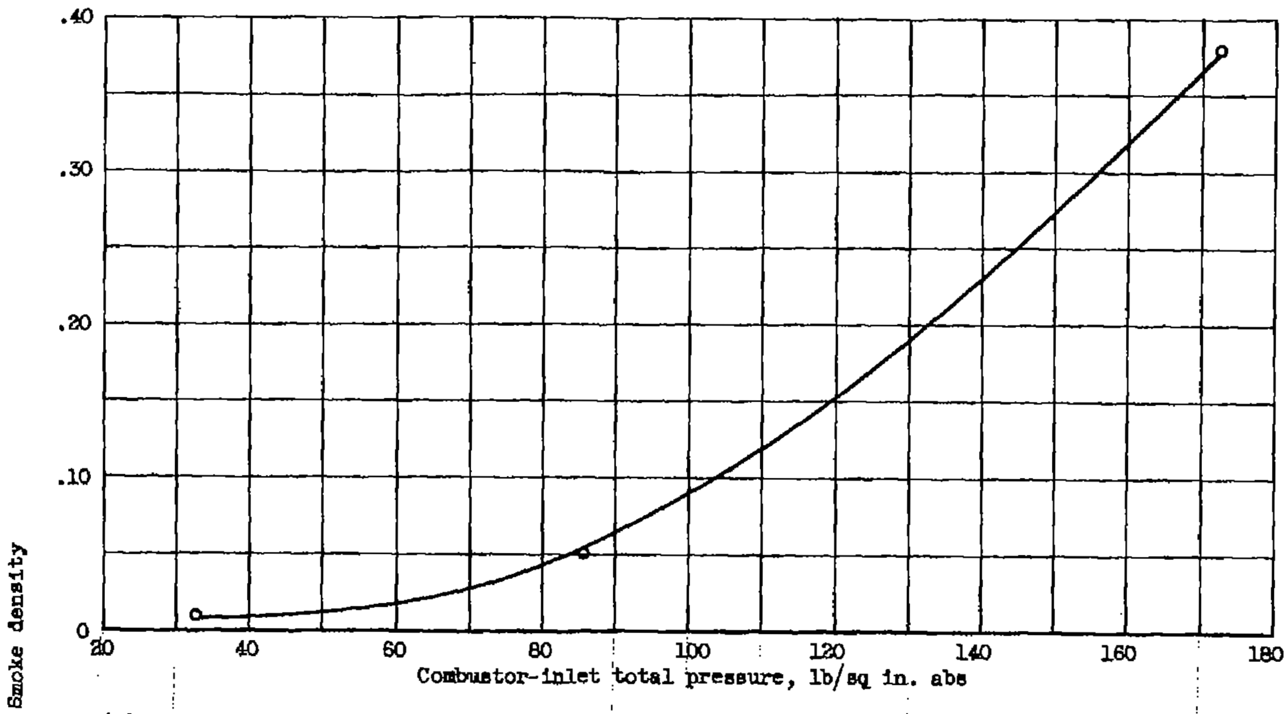


(b) Effect of combustor reference velocity. Inlet-air total pressure, 86.1 pounds per square inch absolute; inlet-air temperature range, 244° to 249° F; fuel-air-ratio range, 0.0168 to 0.0180.

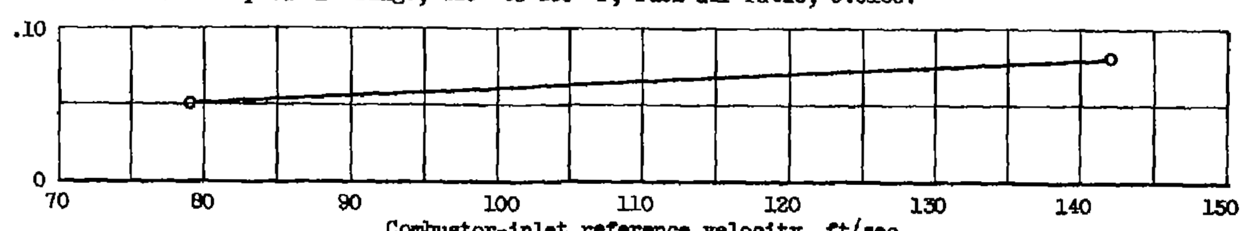


(c) Effect of fuel-air ratio. Inlet-air total pressure, 86.2 pounds per square inch absolute; combustor reference velocity, 78 feet per second; inlet-air temperature range, 239° to 246° F.

Figure 5. - Concluded. Effect of combustor conditions on carbon deposition in single tubular combustor.

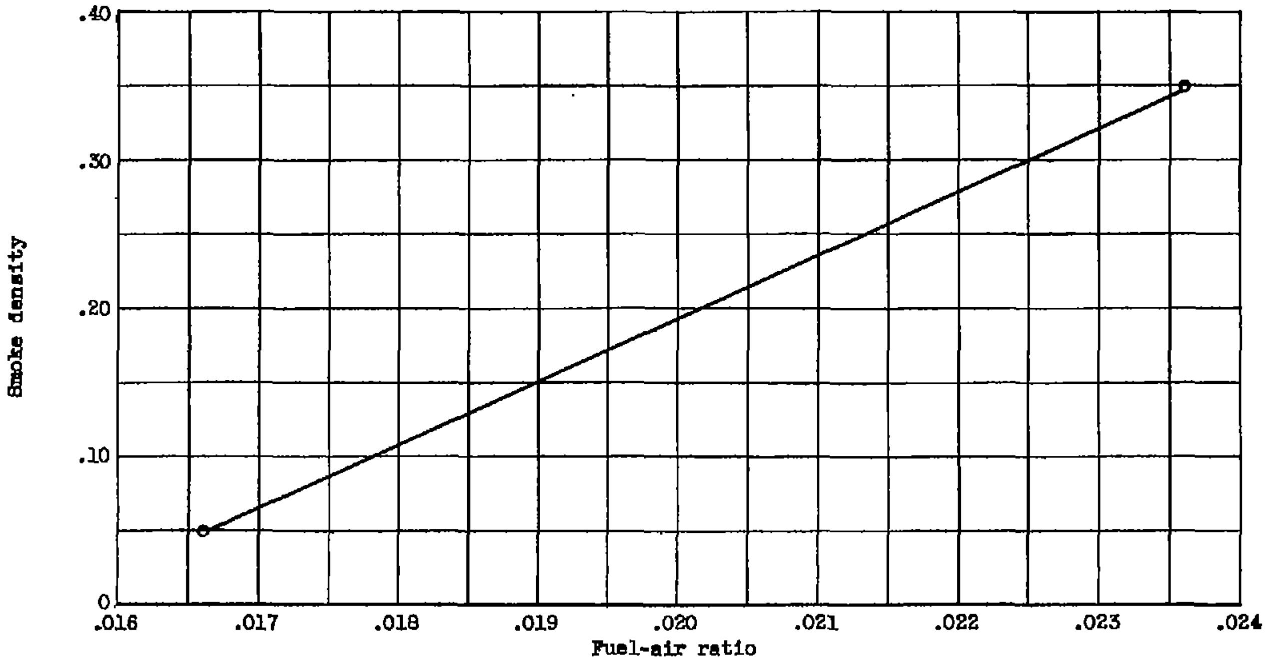


(a) Effect of combustor-inlet total pressure. Combustor reference velocity, 80 feet per second; inlet-air temperature range, 220° to 239° F; fuel-air-ratio, 0.0166.



(b) Effect of combustor reference velocity. Combustor-inlet total pressure, 86.3 pounds per square inch absolute; inlet-air temperature, 236° F; fuel-air-ratio range, 0.0166 to 0.0173.

Figure 6. - Effect of combustor conditions on smoke density in single tubular combustor.



(c) Effect of fuel-air ratio. Combustor-inlet total pressure, 85.9 pounds per square inch absolute; combustor reference velocity, 79 feet per second; inlet-air temperature, 237° F.

Figure 6. - Concluded. Effect of combustor conditions on smoke density in single tubular combustor.

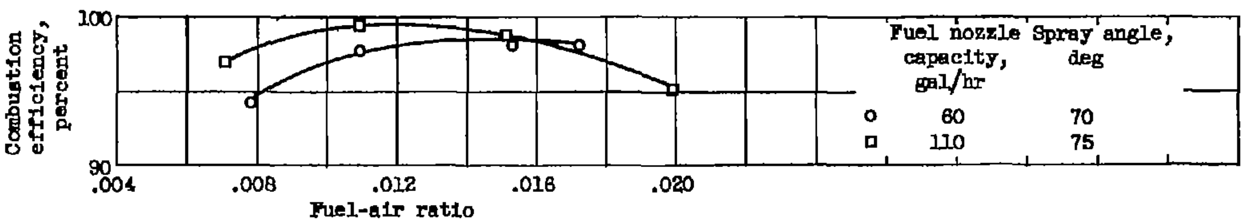
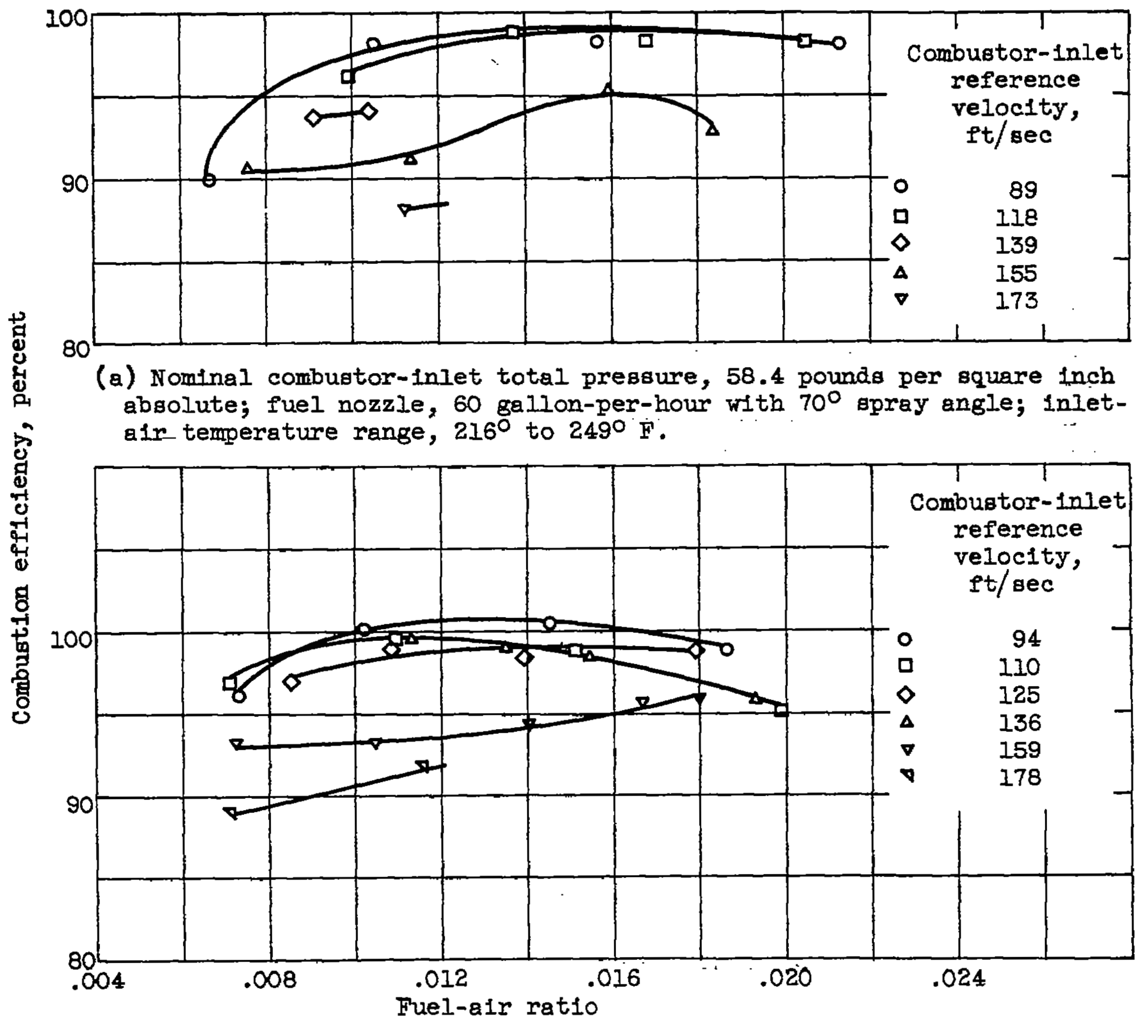
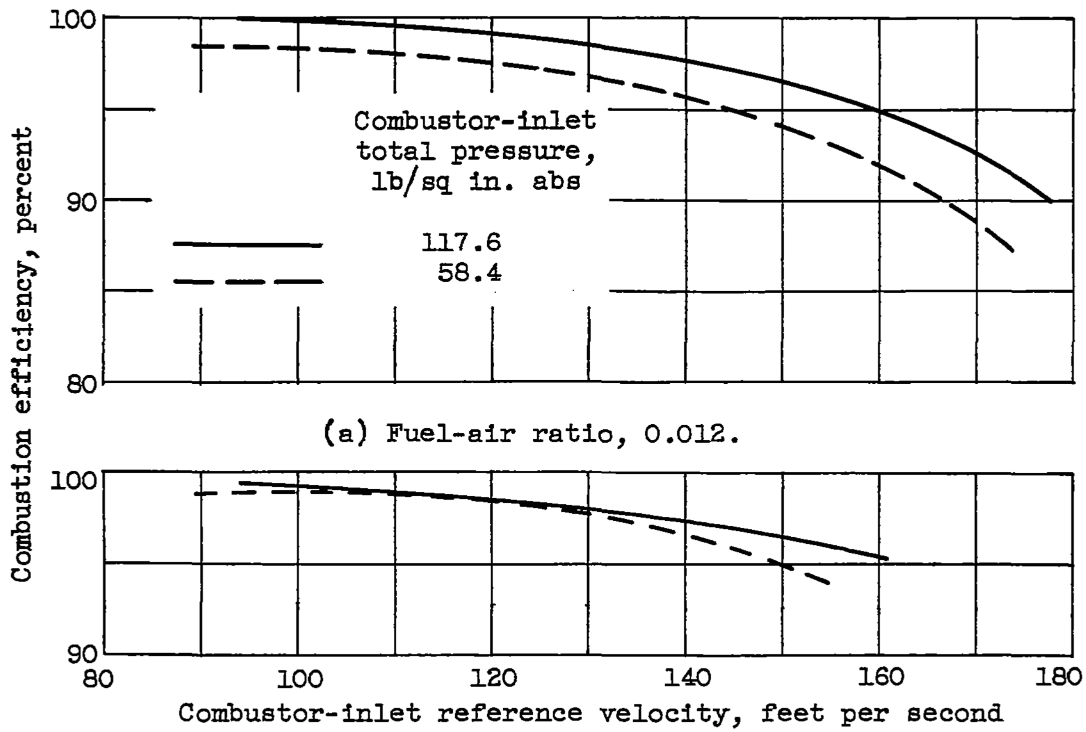


Figure 7. Effect of fuel-nozzle capacity on combustion efficiency in single tubular combustor. Combustor-inlet total pressure, 117.9 pounds per square inch absolute; combustor reference velocity, 110 feet per second; inlet-air temperature range, 241° to 258° F.



(b) Nominal combustor-inlet total pressure, 117.6 pounds per square inch absolute; fuel nozzle, modified 110-gallon-per-hour; inlet-air temperature range, 250° to 258° F.

Figure 8. - Effect of inlet-air pressure, velocity, and fuel-air ratio on combustion efficiency in single tubular combustor.



(a) Fuel-air ratio, 0.012.

(b) Fuel-air ratio, 0.018.

Figure 9. - Effect of combustor reference velocity on combustion efficiency in single tubular combustor.

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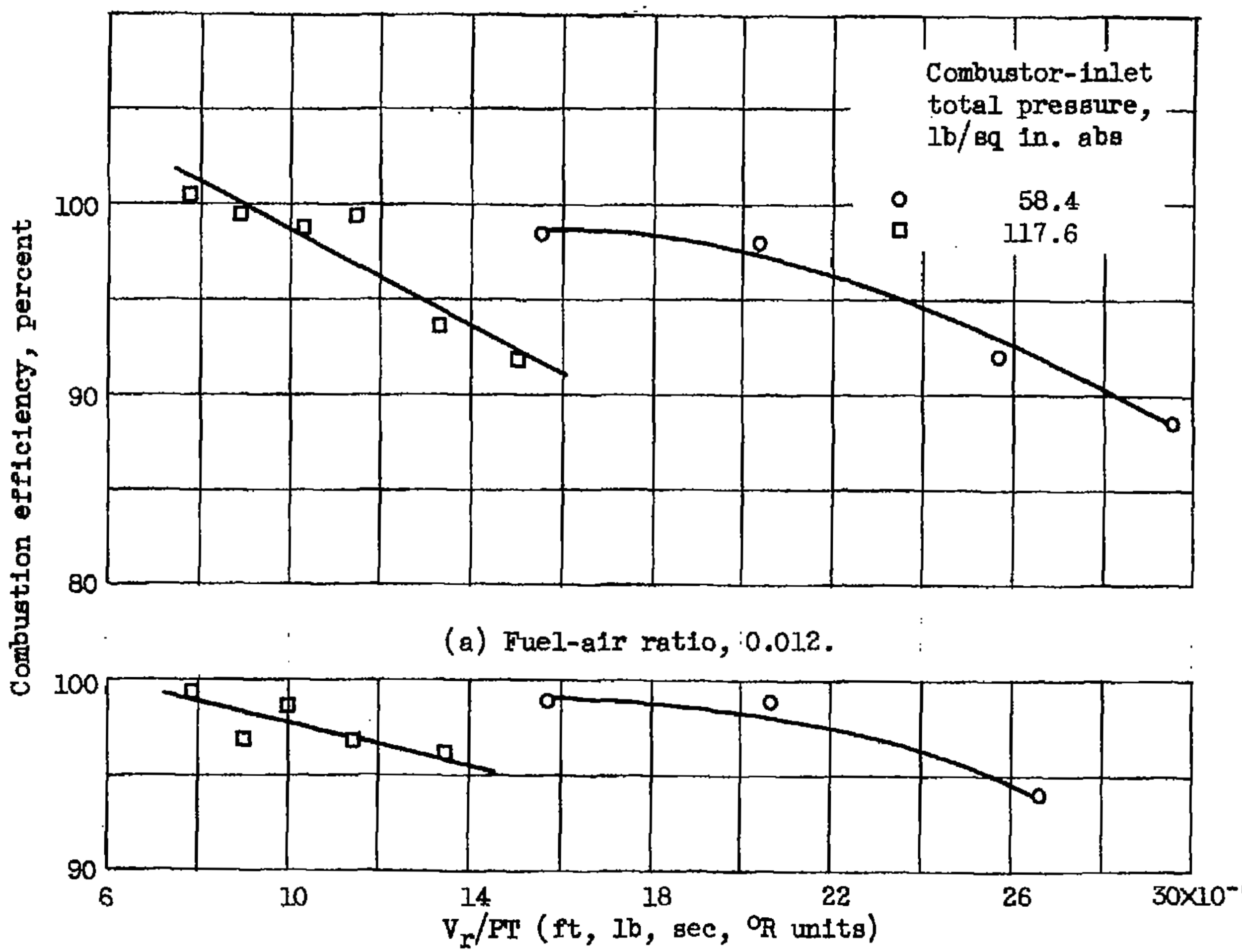

(a) Fuel-air ratio, 0.012.

(b) Fuel-air ratio, 0.018.

Figure 10. - Correlation of combustion parameter with combustion efficiency in single tubular combustor.

[redacted]

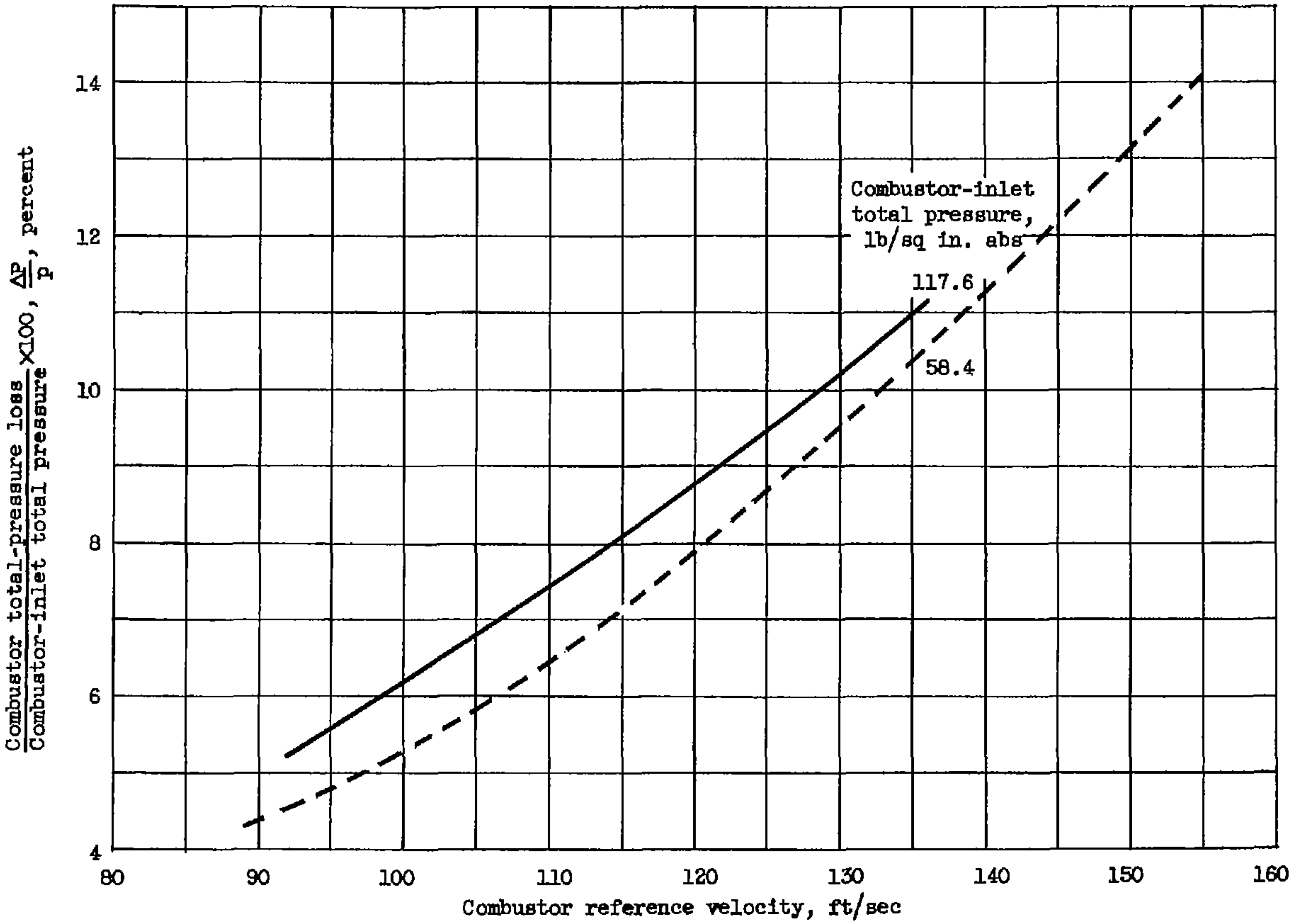

Figure 11. - Effect of combustor-inlet reference velocity on combustor total-pressure loss in single tubular combustor. Temperature-rise ratio, 2.0.

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